Prediction of the Flow-Induced Vibration Response
of Cylinders in Unsteady Flow

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LONG-TERM GOALS

The long-term goal of this research is to develop robust tools for the prediction of the structural dynamic response of long flexible cylinders to vortex shedding.

OBJECTIVES

The long-term goal translates into two specific objectives:

1. The first is to understand and quantitatively evaluate the non-dimensional parameters, which characterize the VIV behavior of cylinders under steady and unsteady, sheared flow conditions. This will depend on analysis of a wide range of field and model test data.

2. The second is to develop new structural dynamic modelling tools that may be used to predict the dynamic response of cylinders at low and high mode numbers.

APPROACH

Our approach is to improve VIV response prediction models by analysis of model test and full-scale field experiment data. Two years ago we began working with data from four full scale drilling risers in the North Sea and two large scale model tests of catenary risers. In the past few months we have just begun to work with data from two full scale catenary risers: one in the Gulf of Mexico and the other offshore Brazil. The ONR funding is used to leverage additional funding from an industry consortium project, which operates in parallel to this one. Its primary objectives are the development of computer programs for prediction of the fatigue life of marine drilling and production risers. The participating companies also provide opportunities for conducting laboratory and full scale experiments, which would otherwise be far to costly to perform. ONR sponsorship allows the Principal Investigator to add long-term, basic research objectives to the often short-term pragmatic interests of the industry sponsors. The result is a synergistic mix of short and long-term research goals.

WORK COMPLETED

Research in the last twelve months has focused in two areas. The first has been the continuing study of VIV response data from full-scale, drilling risers in the North Sea and of full-scale and model test data from catenary risers in steady and unsteady flow. The data from all tests has been analyzed in a

collaborative effort with research staff at other universities and in industry [Cornut et al, 2000, Kaasen et al, 2000, Vikestad et al, 2000]. The second focus area has been the continuing development of response prediction techniques for both long, flexible catenary risers as well as vertical drilling risers.

RESULTS

VIV Response in Periodic Flow. The unsteady response prediction of catenary and lazy wave risers is the subject of two doctoral dissertations. Both are scheduled to finish in the next six months. One of the most useful results so far has been the recognition that the onset of VIV in a periodic flow may be predicted by a threshold Keulegan-Carpenter number. The onset of VIV for spring mounted cylinder in a controlled U-tube experiment is known to be around KC=6. In such a test the cylinder has a single natural frequency and the flow is uniform. In the offshore environment a typical periodic flow condition results when the top end of a flexible riser moves periodically due to the heave motion of the surface vessel. Model tests were conducted in Lake Pend O'Reille. The model was 1.5 inches in diameter and over

Region of maximum velocity and maximum KC
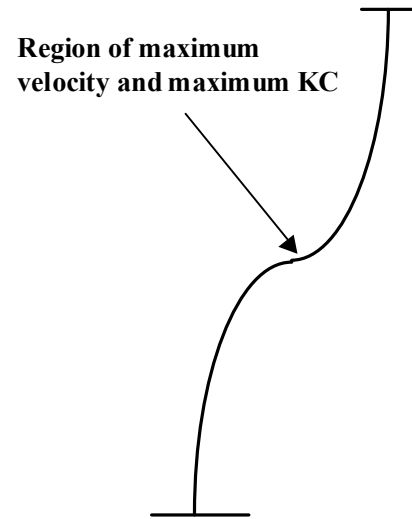
Lake test model configuration
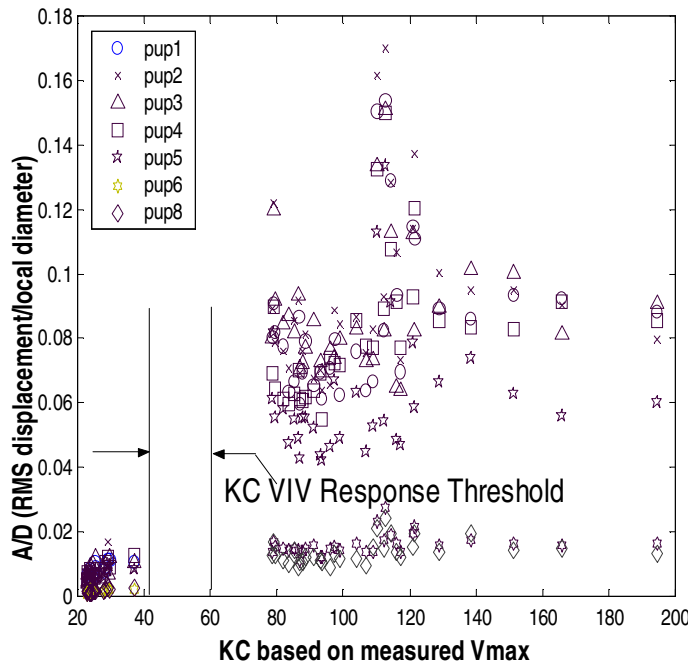
850 feet in length. The model was deployed in a steep S-shaped curve as shown in the figure above. The riser was subjected to periodic vertical motion of the top end, as shown in the first figure. The second figure (left) is a plot of the maximum KC number on the riser versus the maximum VIV response as measured in RMS A/D. The measurement points referred to as PUPs were all in the vicinity of the middle of the S-bend, where the greatest transverse velocity of the riser occurred. As one can see in the plot, significant response did not occur until the KC number exceeded 40. For these model tests the typical responding mode was the 20th to the 80th mode depending on the amplitude and period of the top motion.

Other periodic, motion-induced VIV experiments are being evaluated [Lyons et al, 2000]. A preliminary result is that there appears to be a relationship between the KC threshold and the parameter $n\zeta$, which is the product of the mode number of the responding mode and the damping ratio of the mode. If this number exceeds 1.0 then the behavior of the system approaches that of an infinitely long cylinder and the threshold KC number may be quite high, such as in this experiment with a threshold of 40. When this parameter is less that 0.1 then standing wave behavior is common. For a spring-mounted cylinder in a uniform flow with light damping this parameter is very small and the KC

threshold is at the minimum value of approximately 6. In the latter case the excitation acts on the full length of the cylinder and should be most effective at initiating response. In cases with high $n\zeta$ the excitation region is often only a small portion of the total length and propagation of vibration energy as waves away from the excitation region increases the need for longer duration excitation to initiate VIV. Longer duration is equivalent to higher KC number. Further research remains to be done to refine the understanding of the dependence of the response threshold on $n\zeta$.

Response Prediction and the Significance of the Parameter, S_g. One of the key problems in VIV response prediction in sheared flow has been the prediction of single-mode dominance in sheared flows in spite of many competing modes. This challenge has stimulated a new look into the meaning of the dimensionless parameter, which is known variously as the "response parameter", the "reduced damping" or the "Scruton number". It is known to be a rough predictor of response amplitude A/D. The various forms have small differences and there has been some debate over the years as to which is correct. Most of the controversy centers on the definitions of mass ratio and damping ratio (ζ). Our recent studies have shed some new light on this.

Consider a simple 2D rigid cylinder of unit length, mounted on springs in a uniform flow. It is free to respond in the transverse direction. Assume that the cylinder is vibrating under lock-in conditions and that the lift force in phase with velocity may be characterized as a cosine function with a single frequency at the vortex shedding frequency. This ignores the higher harmonic terms in the forcing function and therefore only addresses the dominant response at the shedding frequency. The cylinder is a single degree of freedom oscillator with the following equation of motion, where we assume that the fluid force in phase with acceleration may be lumped into an added mass term, m_a .

$$(m_s + m_a)\ddot{x} + R_s\dot{x} + kx = \frac{1}{2}C_{L,v}\rho_w U^2 D\cos(\omega_s t) \qquad (1)$$

Under lock-in conditions, the vortex shedding frequency equals the natural frequency.

$$\omega_s = \omega_n = \sqrt{k/(m_s + m_a)} \qquad (2)$$

At resonance $x = A\sin(\omega_n t)$ is a solution of the equation of motion. Substituting in for x(t) shows that the inertial and stiffness terms cancel, leaving the far simpler relationship that follows:

$$R_s\dot{x} = R_s A\omega_n \cos(\omega_n t) = \frac{1}{2}C_{L,v}\rho_w U^2 D\cos(\omega_n t) \qquad (3) \text{ Solving for A/D yields:}$$

$$\frac{A}{D} = \frac{C_{L,v}}{2}\frac{\rho_w U^2}{R_s\omega_n} \qquad (4)$$

The last expression is a simple statement of dynamic equilibrium between lift force and damping forces. It tells us that at lock-in the response amplitude is insensitive to mass ratio. This expression contains a dimensionless group, which characterizes the lock-in response of a 2D cylinder. This parameter is identical to one usually called S_g, providing that the damping ratio and mass ratio are defined in one particular way. The commonly accepted definitions of S_g, mass ratio, damping ratio and Strouhal number are as follows:

$$S_G = 2\pi S_t^2\left(\frac{m}{\rho D^2}\right)4\pi\zeta, \quad mass\,ratio = \frac{m}{\rho_w}D^2, \quad \zeta = \frac{R_s}{2\omega_n m}, \text{ and } S_t = \frac{\omega_n}{2\pi}\frac{D}{U} \quad (5)$$

The usual definition of the mass per unit length, m, in the mass ratio expression is that it is structural mass only. However, to be consistent with the original equation of motion, the mass/length, as it is used

in the definition of S_g above and in the expression for damping ratio, must include the added mass term. That is to say: $m = m_s + m_a$. Upon substituting for S_t and ζ in the above expression for S_g, the mass/length terms cancel out, leading to an expression for S_g, which is not a function of the cylinder mass, as shown below:

$$S_g = \frac{R_s \omega_n}{\rho_w U^2} \quad (6)$$
This is the dimensionless group, which appeared in Equation (4). Restating

equation (4) and expressing it in terms of S_g leads to:
$$\frac{A}{D} = \frac{C_{L,v}}{2}\frac{\rho_w U^2}{R_s \omega_n} = \frac{C_{L,v}}{2 S_g} \quad (7)$$

Solving for $C_{l,v}$ leads to the following equation of a hyperbola:
$$C_{l,v} = 2 S_G \frac{A}{D} \quad (8)$$

On a linear plot of Sg versus A/D lines of constant lift coefficient are hyperbolas, which form straight lines on a log-log scale. The last figure is such a log-log plot with the lines of constant $C_{l,v}$ shown. Also shown is a broad swath, which is the region where much experimental data exists, as compiled by Owen Griffin[1984]. Thus, a consistent use of the mass/length in the response calculation has lead to an explicit relationship between the parameter S_g and the lift coefficient in phase with velocity. Although developed for the spring mounted cylinder, this analysis may be adapted to the multi-mode, sheared flow case as shown in reference [Vandiver, 1985].

Lift Coefficient in Phase with Velocity at Lock-in
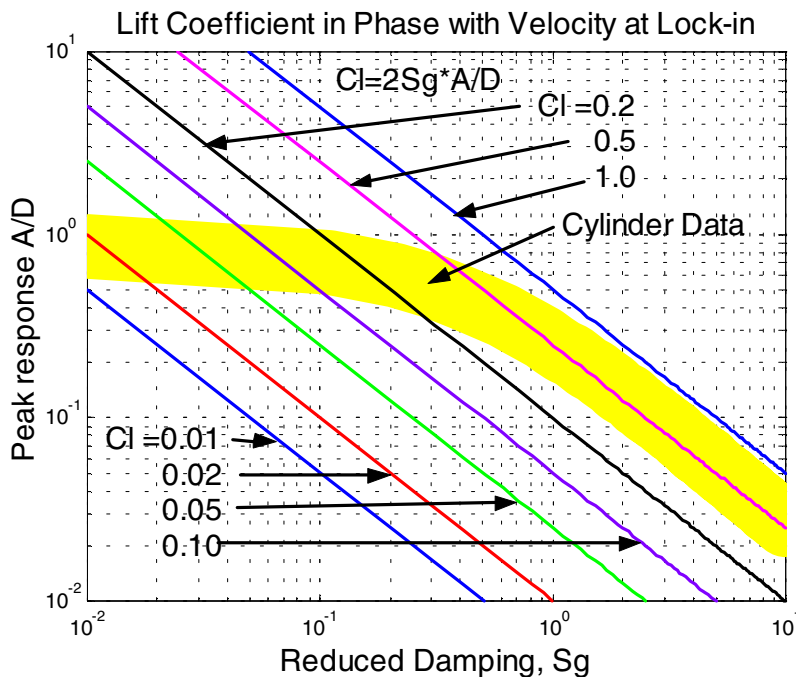
IMPACT/APPLICATIONS

The results of this project will be useful to the designers of ocean structures exposed to current. Vortex-induced vibration of oil exploration and production risers is often the primary limiting factor in the determination of the fatigue life of the riser. Present state of the art fatigue life prediction models are overly conservative because they are not yet calibrated for many important effects. Model test and full-scale riser response data will be used to calibrate the computer programs used in design of these systems.

TRANSITIONS

The data from the model test and full-scale experiments are being used to calibrate the program SHEAR7, which was written by the PI and his students and is being used by approximately thirty-five companies and universities. A new release of the program with major improvements will occur late in the 2000 calendar year.

RELATED PROJECTS

2H STRIDE Measurement Project. This is a consortium project run by the company 2H Offshore in the UK. In the last year a catenary-drilling riser in the Allegheny field in the Gulf of Mexico was instrumented with approximately 12 accelerometer packages. The PI will be able to have access to this data to calibrate response prediction programs.

2H has recently conducted another experiment, which investigated the vibration boundary condition of a catenary riser as it comes in contact with the seabed. The PI was a consultant to that project and will use the results to improve dynamic models of the bottom boundary condition at the touchdown point of catenary risers.

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